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DIASTROPHISM AND THE FORMATIVE PROCESSES. II[1]

SHELF-SEAS AND CERTAIN LIMITATIONS OF DIASTROPHISM

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It will doubtless be agreed at once by all that the general configurations of the oceanic beds are due to deformative processes. There will be a readiness also to agree that the same is true of the beds of some of the seas and minor water bodies. On this background of common opinion we may discuss sea-beds that do not owe their final form to diastrophism but to gradational processes. If all of the former class, large and small, be grouped as diastrophic basins, all of the latter class may be styled gradational basins, however incompletely the term basin represents their forms. There are of course composite and erratic forms that may be neglected here. The most familiar examples of the gradational type are the continental shelves. These are here regarded as only initial forms of the type, falling far short of serving as ideal representatives of the maturest class of sea-shelves. The waters that rest upon these sea-shelves may be known conveniently as shelf-seas.

The ideal shelf-sea is not independent in origin; it is conditioned by the diastrophic sea from which it grows; diastrophism shapes the original basin; gradation superposes certain characters and extensions upon it. These new features are of radical importance in biological and stratigraphical development.

Not only are shelf-seas conditioned at the outset by diastrophism but their histories hang on its continuous or its periodic action. If diastrophism is continuous, the gradational process constantly suffers disturbance and is ineffective; if diastrophism is periodic, gradation goes forward on given lines as long as quiescence continues attaining greater and greater degrees of maturity of type, ceasing only when its systematic work is cut off by renewed diastrophism. If diastrophism is periodic, effective gradational results are inter-periodic products; diastrophism and systematic gradation are alternately dominant. From these general considerations, let us turn to specific features.

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[1] This article is nearly identical in substance with a portion of a paper read at the Twelfth International Geological Convention, Toronto, Canada, August 16, 1913.

The distinctive characteristics of shelf-seas are these:

1. *There is a close approach to parallelism between the surfaces and the bottoms of these seas.* There is but a gentle slope between their landward sides and their seaward sides or their deepest axes. In their immature stages the typical slopes may be 1 in 1,000 or 1 in 800 or steeper; in their maturity the slopes seem often to have fallen to 1 in 2,000 or 3,000 or lower. This close approach to parallelism between surface and bottom is a feature of moment in its bearings on the nature of the deposits and the character of the life.

2. *The parallelism between sea-surface and sea-bottom is close in the further sense that the two planes lie near one another.* For reasons inherent in the gradational processes, the sea-shelf is limited in depth. Beyond a certain depth of water effective transportation of sediment fails, and the further growth of the shelf is checked except as the deep in front is filled. For the limital depth, let us assume 600 feet, 200 meters, 100 fathoms, the recognized mean depth of the outer edge of the present continental shelf. Let considerable variations from this be recognized as consistent with the type, but this figure may serve as representative. Exactness in this particular is not material to the purposes of this discussion, for the distinctions to be drawn are so broad that great latitude is permissible without invalidating the arguments built upon them. The natural criterion of the type is that depth at which the agitation of waves, tides, and currents ceases to keep in effective suspension or in rolling condition so much of the terrigenous silts as constitute the larger mass of the earthy matter derived from the land. The extremely fine material that may float long and far with little motion is negligible as it does not build up the bottom on which it falls apace with the more bulky constituents. The shelf is thus a product whose configuration is determined by its own conditions; it is a self-regulated formation; the guiding element in whose genesis is the sea-surface and the agencies that play upon it.

3. *The sea-shelf is definitely correlated with the penetration of solar rays.* This is a relation of biologic moment. As the mode of formation keeps the face of the shelf within a certain distance from the sea-surface, the waters upon it have a rather definite range of illumination. Competent opinion places the larger part of the effective photo-synthetic action within a hundred meters of the surface, while photographic effects vanish at three or four hundred meters. Organisms that depend on insolation, or that live upon those that do, may be assumed to be rarely fossilized at greater depths than these when there is no ground to suspect postmortem transportation. The shelf-sea deposits therefore embrace the sessile photo-synthetic types and their dependencies. Deeper deposits may embrace the pelagic types, but rarely the sessile and quasi-sessile forms. The shelf zone is therefore from the very nature of the case a biologic horizon of the first importance. Its faunas in consequence belong to a distinctive type. The life entrapped in the bed of the shelf-sea is demarked from that caught in the abysmal bed of the ocean.

There is, however, a narrow belt about the borders of diastrophic seas that enjoys photo-vital conditions much the same as the gradational shelves, though the slopes are normally steeper and the life-conditions somewhat more special and precarious in general. A comparison of the relative values of the gradational shelves and the diastrophic belts within the same depth-limits is a critical part of this study and will be taken up presently. It thus appears that the shelf-seas are photobathic zones of special effectiveness, and are, and no doubt always have been, the habitat of a most important type of marine faunas and floras, the class most akin to the life of the land—pre-eminently the class on which the divisions of geologic history have been based, and may best be based still more specifically, so far as these divisions are biologic.

4. It is scarcely more than a reiteration of the last statement in a special form to say that the faunas of the shelf-seas of ancient times were given distinctive aspects by the conditions of insolation, of aeration, of low pressure, and of agitated bottom, all of which were determined by the mode of origin of these seas. These sea-conditions became, therefore, critical factors in the history of

ancient life. The extent and maturity of these seas has been a decisive factor in geologic history.

5. So too it is scarcely more than reiterating the statement that preceded the last to say that the typical sediments of the shelf-seas at all geologic ages were of the types that depend on agitated waters. The sediments were assorted and spread out with notable uniformity, continuity, and exceptional horizontality over wide tracts because of the conditions of formation.

6. *The shelf-seas were spread upon the continental platforms.* Diastrophic sea-basins may be *set in* between continents (Mediterranean, Caribbean, etc.) or be *sunk within* the continental platforms, but the gradational seas lay upon terraces either built out from the upper edge of the continental platforms or cut back on the upper edge of the platforms, or else were flooded forth upon the lower parts of the platforms by the partial filling of the ocean basins with sediment. They were technically epicontinental, while the diastrophic seas were usually intercontinental or intracontinental. Of course shallow diastrophic basins may be so formed as to be in a sense epicontinental, but not in the constructive sense here applied to the sea-shelves, and of course there were composite types not belonging wholly to either class.

7. *Abandoned beds of shelf-seas were transmitted to later periods, sometimes intact, oftener mutilated, and thus became important inheritances.* Diastrophism may affect distant ocean basins, increasing their capacity and drawing off the waters from above a sea-shelf, leaving it intact. The shelf may continue to escape disturbance until the inwash from all the lands of the globe so far fills the common sea-basins as to lift the sea-surface and force the waters to return upon the abandoned sea-shelf, introducing a new period of sedimentation in close conformity to the old one. Oftener the sea-shelf participates in some degree in the deformation, however preponderant it may be in distant regions, for the earth body is a physical unit and great deformations in one quarter are likely to have a greater or less effect in other quarters. The sea-shelf inherited by the following period has usually been warped in some notable measure and the later terrane is somewhat discordant with the earlier one. And yet the gradational work of the earlier period

is an inheritance of great moment. The work of regrading in the later period is relatively light and the later sea-transgression much facilitated. Even when the deformation between the periods is strongly felt within the same continent, it is usually confined to portions of the transgressive plane only and the rest remains available for the next sea advance. For example, the Mid-Ordovician transgression formed a broad shelf covering half America; this was only partially warped on its east border by the Taconic folding, and the transgression of the Mid-Silurian was greatly facilitated by its inheritance from the Ordovician. The Ordovician had received a great inheritance from the Cambrian shelf-work. The work of all these was handed on to still later periods. This leads us to note an additional characteristic.

8. *The work of shelf-seas was cumulative.* This is true also of base-planes, the working copartners of shelf-seas, but not in an equal degree. An uncovered base-plane is constantly affected by disintegration and on any upwarp to destructive erosion against which it has no protection. The shelf-sea work is constructive and on any upwarp is defended by its own deposits. While it suffers, it has resources of resistance. In addition to this, its attitude is conservative and some notable uplift is necessary to expose all its strata to removal. It thus follows that a great sea-shelf once formed usually transmits its results to successive periods, and each of these adds its own extensions. There is thus developed a succession of sea-transgressions recorded by terrane spread upon terrane, making up a series which is continuous until one of the greater diastrophisms cuts the cumulative process short.

9. *The upper faces of the continents are largely the products of the cumulative work of the shelf-seas, though much mutilated by diastrophism and erosion.* It seems safe to say that 80 or 90 per cent of the surface areas of the continents bear some evidence of former shelf-sea work and 70 per cent or more are still mantled by the shelf products, though some notable part of this mantle has lost its original flat attitude. The relatively plane upper face of the continents is to be assigned largely to base-planing and shelf-sea work in which the latter has left the more lasting, if not the greater, product. Shelf-sea work is pre-eminently a process of terracing.

It is a natural result that the continents are pre-eminently the great terraces of the globe. The picture of the continents as essentially terraces wrought upon diastrophic embossments is no doubt the truest that can be formed, and the contest between the diastrophic forces that emboss by protrusion and the gradational forces that terrace by planation and shelf-building, the chief physical battle of geologic history.

Diastrophic limitations.—Let us now consider the degree of competency and of incompetency of diastrophism to produce shallow seas whose deposits and faunas may be comparable in any serious sense with those of the shelf-seas.

If the earth-body were a perfect spheroid of revolution completely adapted to its own conditions, and if the volume of the hydrosphere were essentially what it is today, there would be a perfect parallelism between the sea-surface and the sea-bottom of the universal ocean that would be the inevitable consequence of these conditions, but there would be no sediments of the common kinds nor any life of the more familiar fossil types, but only the pelagic and the abysmal. The picture of such a state of the earth and of such an evolution as might arise from it, if indefinitely prolonged, is as far as possible from that which geologic history really presents at any known age. The actual earth has a deformed surface of such proportions that about one-third is continental protuberance and two-thirds abysmal depression, with connecting slopes between. At present about one-sixth of the continental protuberance is covered by epicontinental seas, and this sixth adjusts the one-third-two-thirds ratio to the more familiar one-fourth-three-fourths ratio of land to water so successfully inculcated by the geographies. It is the one-third-two-thirds ratio of body-protuberance to body-depression that concerns us in deformative studies. In *these* studies the modification imposed by the sea-shelf work is an incident.

These proportions have been taken of course from the present status. If it is suggested that a quite different ratio may have prevailed in early geologic times and that the ratio in the Paleozoic era may have been so far different as to leave little value in this present ratio, it is a ready reply that no special weight is placed on this ratio as such. It is merely convenient for use in forming a concrete conception of the work of deformation taken in its largest sense. It is my belief, however, that the ratio of protuberance to depression as defined by the sea-level has not radically changed from the beginning of the Paleozoic to the present time, but geologists entertain varying opinions on this point.

It is becoming more and more clear as study proceeds that the great deformations that determine the ocean depressions and the continental protuberances are not mere superficial incidents of the earth's development. One of the latest geodetic inquiries into the distribution of gravity finds that the outer part of the earth in the United States reaches a state of isostatic equilibrium only at a depth of seventy odd miles, even when an extreme hypothesis of the distribution of differences of specific gravity is made the basis of interpretation.[1] If a natural dying away of the differences of specific gravity from the surface downward is made the basis of interpretation, the depth is much increased and may be more than doubled. The geodetic data of India, a land of great deformations, seem to demand much greater depths than the data of America.[2] Considerations that lie in the mechanics of the case strongly support the view that the portion of the earth that is involved in the highest order of deformations is both thick and stiff.

Now in the deforming of a spheroid whose yielding parts are so deep and stiff as to take on and maintain broad inequalities like the continents and oceanic basins, certain mechanical methods are inherent and inevitably express themselves in the resulting configurations; for example, the portions that are most nearly horizontal will in the nature of the case be those at the bottoms of the sags and the tops of the swells. These portions may be nearly tangent to horizontal planes, but the dips of the intervening surfaces will naturally become increasingly greater toward points midway between the swells and sags, or at least somewhere between them. If, therefore, the sea-surface lies at such a position that one-third or one-fourth or some considerable fraction of the upper portion of the warped surface is above it and a still larger fraction, two-thirds or three-fourths or some such fraction, lies below it, the zone of shallow water will usually cut the warps at points where they have relatively high dips. The area between the water-surface and the shelf-limit in depth will therefore be proportionately small. For a rough illustration, if the average crests of the continental swells be taken at the modest figure of 6,000 feet above sea-level and the average bottoms of the oceanic sags at 18,000 feet below sea-level, the vertical depth of 600 feet spans only one-fortieth of the total range. The value of this fraction has yet to be reduced for the excess of slope of this portion over the mean slope to give the horizontal breadth of the belt really embraced within the shelf-depth. At the present time the extreme range of deformative heights and depths is more than twice that selected as the basis of this illustration.

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[1] John F. Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States," *U.S. Coast and Geodetic Survey*, Washington, D.C., 1909.

[2] G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India.* Calcutta, 1912.

An inspection of present conditions seems to show that the sea surface so cuts the normal unmodified diastrophic surfaces that an area not more than half that of the present continental shelf would lie between the contours of zero and of 600 feet depth, or perhaps 2.5 per cent of the earth's surface. This differs radically from the broad areas of shallow water that obtained at the climax of the great sea-transgressions in Paleozoic times when from 40 per cent to 50 per cent of the surface of the North American continent was covered, i.e., from 16 to 20 times as much, and more or less comparable portions of other continents were covered in a similar way and at the same time. That these transgressive seas were shallow is implied by the sediments and by the faunas alike.

Various other modes of inspection lead to results of like order. The discrepancy is so great that the elements of the estimate may be liberally changed to cover all legitimate sources of doubt without affecting the general tenor of the results.

If the borders of the continents be thought to be affected by faulting in some special degree, the incompetency of diastrophism to give these nicely adjusted shelves will be emphasized rather than mitigated, for the usual effect of faulting is an increase of the abruptness of the descent from the land to the deep sea.

These facts seem, therefore, to force the serious consideration of the *proposition that the ordinary diastrophism of the earth is not suited to give the shallow-water seas which the geologic record so abundantly presents for interpretation.*

If to escape the force of this proposition one indulges the inherited habit of assuming that a flat area from the sea-bottom "might have been" lifted to just the right height or let down from the land area to just the right level for this specific shallow submergence, it is well to note that the right height is only a small fraction of the full range of height involved in deformation and that the chances of the close adjustment required are correspondingly small, and should be correspondingly infrequent as well as irregular in distribution, whereas the actual case presented by the geologic seas is a systematic repetition of this state from period to period, combined with similarity of action in different continents.

If one indulges in the familiar old idea of a slow subsidence to the sea-level and below, he takes refuge in the most plausible of all diastrophic devices for meeting the actual case. In pure theory, a downward diastrophic movement has little advantage over an upward one in meeting the demands of this case. A downward movement is, however, supplemented by gradation. It is commonly assumed in such a case that the deposits build up the sinking area as fast as it descends and thus preserve an adjustment to the sea-surface. Now if the rate of deposition and the rate of subsidence were *inherently correlated with one another* so as to be co-operative in the same phase, such an adjustment would be natural and be often repeated and so meet the requirements of the case to this extent. If, for example, the weighting due to deposition were sufficient to cause proportionate subsidence, the adjustment would be easily and naturally maintained when once made. This would happen if the earth-surface were in free isostatic adjustment to this degree of nicety and the stiffness of the crust offered no effective resistance to continuous warping. On the adjacent land, however, whence the material for the deposit is being taken, the unloading should cause a proportionate rise and the sea transgression be defeated.

If, however, general elevations and subsidences are dependent on differential stresses in the body of a very stiff elastic earth capable of accumulating strains of high value, the case is very different, for in such case the crust movements are not immediately responsive to loading and unloading. These can induce only a slight elastic strain in the elastic body. No nice adjustment to deposit can be assumed in this case. In my judgment the phenomena of geology and related sciences support this view and are distinctly opposed to a concurrent adjustment to loading and unloading of the degree of nicety required for the assigned work.

A close adjustment in response to loading and unloading seems on first thought to be supported by views of isostasy that have recently been put forth on the basis of elaborate studies of geodetic data,[1] but this seems to me an untenable application of deductions very important in their true implications, for such a degree of pliancy seems entirely inconsistent with the maintenance of the continents even on the basis of complete vertical isostasy, as will appear from considerations offered in a subsequent discussion, for any type of sostasy that is consistent with the existence of the continents and oceanic basins, as they are, *involves great lateral unbalanced stresses.*

The protuberance of the continents and their repeated rejuvenations when worn down can be explained, it would seem, only on the supposition that the mean specific gravity of the continents is lighter than that of the sub-oceanic segments. This is the postulate of isostasy. Pendulum observations confirm it. It is common ground where diverse views meet.

Now the continents are always being denuded by the mechanical action of wind, water, and gravity on the surface, and by the solvent action of water reaching to notable depths. The protuberances are not only being cut away, but are being leached all the time. There is no real weighting of the continent as a whole under normal conditions. The only apparent weighting is due to that fraction of the sediments that lodges somewhere on it in its course to the great deeps. This fraction is gathered chiefly about the edges of the continent and the weighting there is only a fraction of the unloading of the continent as a whole. The continent as such is being constantly lightened, and if it was in previous equilibrium its constant tendency is to rise. If it can be supposed to have been previously lifted beyond the point of equilibrium it would first be reduced to equilibrium, after which rise would follow. The most that is to be rationally assigned to the weight of sediments on the continental borders is a downward bending of the edges while the adjacent land surface rises under denudation, involving a local tilting of the surface toward the sea. The mechanism thus pictured offers no good ground for the explanation of a great sea-transgression. That the normal tendency of the continents is to rise and has been so throughout geologic history is attested by their continued existence in spite of the constant removal of their material, as also by their periodic rejuvenation and by the continuity of the land life since it began its record. If effective subsidence had habitually co-operated with denudation the disappearance of the continents would have been inevitable. The process of subsidence is not, therefore, normal to the continents. (Subsidence is of course here used in the conventional sense, subsidence relative to the mean earth surface. The mean surface itself may of course approach the center without affecting this relation.) Local or regional subsidence occasionally akes place, but for the continents it is exceptional rather than normal. Apparent subsidence is a common phenomenon arising from the filling of the oceanic basins and the lifting of the sea-level. Local subsidence, as one of the features of warping and faulting, is of course presumed to be nearly as common as the warping itself, but it is of course connected with a complementary uplift. Subsidences of these local types are not tributary to the parallelism and wide extension of the great marine deposits nor to the life adaptations of the great transgressive seas. The consistent elucidation of these constitutes the supreme problem of the geologic seas.

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[1] Hayford, *loc. cit.*

There seem therefore to be very cogent reasons for abandoning the traditional view that the systematic sedimentations and the systematic evolutions of faunas of the higher order are to be assigned directly to vertical or epeirogenic movements of the earth's crust.